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Tephra Influence on Spokane-Flood Terraces, Bonner County, Idaho

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ABSTRACT

In a previous study, our team described five Pleistocene Spokane-flood terraces with a ridge-and-trough surface topography in very gravelly outwash deposits we thought differed in age by <2000 years, but others later found to differ by about 6000 years (19 000 and 13 000 ^{14}C yr BP). Given the possibility of a longer time difference for soil development before deposition of any tephra, we obtained analytical data and reexamined the study thinking that an age difference of 6000 yr would have implications for soil classification and possibly suggest new series. Holocene tephra in the very fine sand (vfs) fraction (0.05–0.10 mm) ranges from 1% in the ridges to 93% in the troughs. The mean of the vfs fraction tephra content of soils on ridges of the higher, and presumably older, terraces (11%) is significantly less than that of soils on ridges of the lower and younger terraces (45%). The mean tephra content in the troughs (77%) does not vary by terrace level. The maximum fine-earth (<2 mm) allophane content of the youngest ridge is 96.3 g kg^{-1} and that of the youngest trough is 95.4 g kg^{-1}. These amounts are greater than five times those of ridge soils on the older terraces. Only about 20 to 50% of the estimated Mount Mazama tephra fall remains on the older Bonner and Kootenai soils, whereas the older Rathdrum soil retains about 400% of the estimated Mount Mazama tephra fall. Minor amounts occur in the Histosol on the flood plain. Isotic 50- to 100-μm thick coatings on some A and B horizon sands indicate that weathering has been minor. Low spodic-horizon indicators (Al_o and Fe_o in subsurface horizons), and high ammonium oxalate extract optical densities of surface horizons, also suggest no fulvic acid leaching. Below the tephra influence, however, the outwash grains have anisotropic clay minerals showing that some weathering may have occurred before deposition of the tephra. The higher allophane content, higher NaF pH, and higher P-retention of lower terrace ridge soils, as compared with higher terrace ridge soils, results mostly from variation in the amount of their tephra and now justifies classifying ridge soils on higher and lower terraces into different taxa and opens the possibility of differentiating soil series by terrace level.

The catastrophic Spokane floods of the Columbia River system produced large outwash terraces in northern Idaho. These terraces mark repeated breaching of ice dams as Glacial Lake Missoula drained. At its maximum, this Wisconsin-age lake was about the size of present-day Lake Ontario (Waitt, 1984). As ice dams repeatedly failed, catastrophic floods flowed westward creating the coulees and other features of the "Channeled Scabland" (Bretz, 1923; Baker, 1973; Bunker, 1982; O'Connor and Baker, 1992) of eastern Washington and deposited terraces along the main stem of the Columbia River including the Hoodoo Valley outwash terraces (Fig. 1 and 2).

Parsons et al. (1981) considered the time interval for deposition of the Hoodoo Valley flood terraces to be ≤2000 yr based on the maximum age of the Winkel surface (10 850 yr) and the age of the St. Helens S set tephra (13 000 yr). The assumption was made that previous depositional surfaces from earlier floods may have been removed by subsequent outwash episodes in the confining valley. This assumption was supported by abrasion marks on the bedrock valley side slopes up to 300 m above the valley floor. The morphological differences in soils across the terraces also favored this interpretation. The earliest and latest ages of Glacial Lake Missoula floods have since been revised and discussed by several authors (Waitt, 1984; Atwater, 1987; Steele, 1991). Atwater places the oldest flood age at 19 000 ^{14}C yr BP. The last flood was about 13 000 ^{14}C yr BP (Mullineaux et al., 1978; Bunker, 1982). The latter flood age is supported by a peat radiocarbon age of 13 080 ± 300 ^{14}C yr BP and from correlated tephra layers (Mullineaux et al., 1978). Some authors have correlated Mount St. Helens S set tephra dated 13 130 ± 350 ^{14}C yr BP found in slackwater sediments with the last flood episode (Bunker, 1982; Mullineaux et al., 1978). Therefore, the sequence of outwash terraces in Hoodoo Valley could have occurred within a period three times longer than Parsons et al. (1981) had considered.

Since the last flood, several tephra deposits from different volcanoes have been identified including Mount St. Helens S set tephra about 13 000 ^{14}C yr BP; Glacier Peak, Washington tephra about 12 000 ^{14}C yr BP (Mullineaux et al., 1978); Mt. Mazama tephra about 6600 ^{14}C yr BP (Richmond et al., 1965); Mount St. Helens Y and W sets tephra about 3200 and 500 ^{14}C yr BP, respectively (Crandell et al., 1962); and the Mount St. Helens 18 May 1980 eruption. It is probable that tephra from most of these named eruptions have crossed northern Idaho and are to be expected in soil surface horizons thus producing a degree of soil welding (Ruhe and Olson, 1980). In the soils tephra thicknesses range from 15 cm for Mazama to a few millimeters for the others (Parsons et al., 1981). Hence, exposure time for the tephra may be considered to span 6000 to 7000 yr, and its presence may dampen the influence of geomorphic age differences of the terraces. Parsons et al. (1981) concluded from field evidence (soil color, texture, and structure) that soils with similar degrees of development occur on the five older terraces. Herein we use analytical data to reevaluate their conclusions, and assess the possibility

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Abbreviations: CEC, cation-exchange capacity; OC, organic C; vfs, very fine sand.

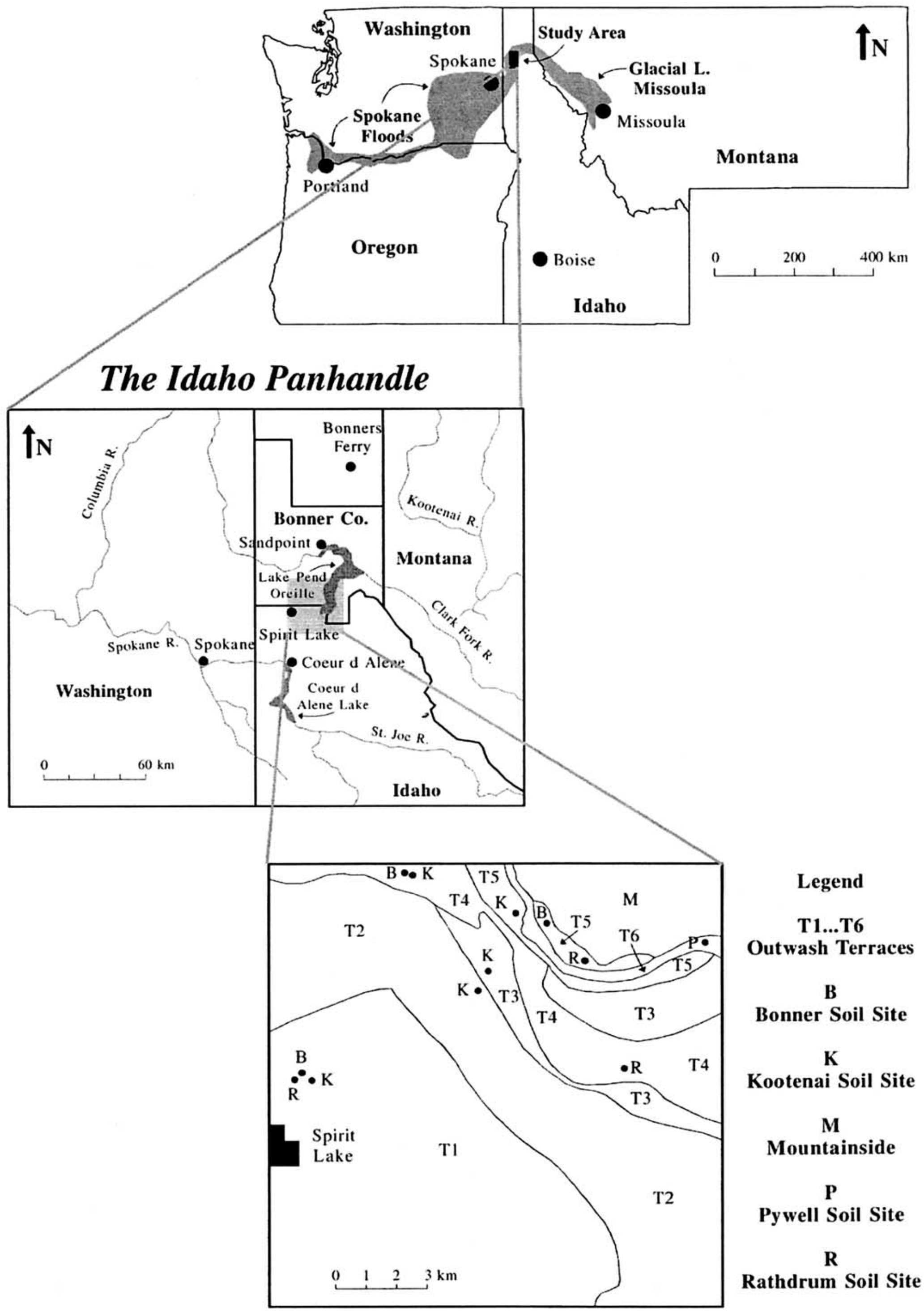

Fig. 1. Location of Bonner County and the study area near the town of Spirit Lake in the Idaho panhandle (Based on Parsons et al., 1981, Fig. 1 and 2).

that soil properties vary enough to justify differentiating soil series by terrace level.

MATERIALS AND METHODS

Soils and Their Classification

The three major soil series occurring on the five outwash terraces are Kootenai, Bonner, and Rathdrum (Weisel, 1982). On the lowest surface (T6), there also are areas of Pywell muck. The mineral soils all formed in tephra-influenced sediment over outwash material. Kootenai soil series are Ashy over loamy-skeletal, glassy over isotic, frigid Typic Vitrixerands. They occur on the crests of the current ripples and are most extensive on T1. Bonner soil series are Ashy over loamy-skeletal, aniso, glassy over isotic, frigid Typic Vitrixerands (Fig. 3). They occur on lower sideslopes and toeslopes of gravel ridges. Rathdrum soil series are Ashy, amorphic, frigid Typic Udivitrands

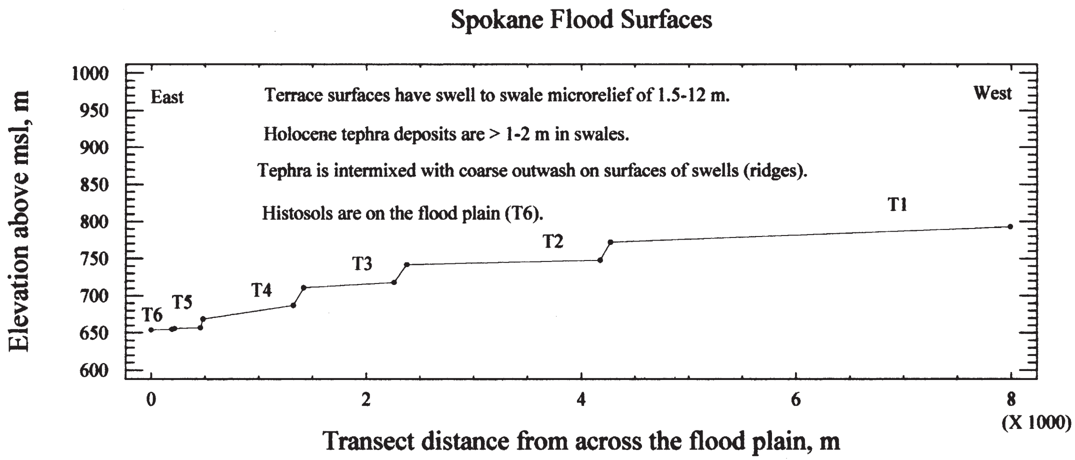

Fig. 2. Transect across the study area from Hoodoo Creek on the east to Spirit Lake on the west.

(Fig. 4). They occur in current ripple troughs and closed depressions where tephra has accumulated to depths of about 1 m. The Pywell soil series are Euic, frigid Typic Haplosaprists on flood plains with high water tables. Parsons et al. (1981) described the geomorphic setting, climate, and vegetation of these soils. Over 80% of the precipitation occurs during the frost season, most of it as snow (Kincer, 1941). The classification of the series given here (the 22 Aug. 2004 Official Soil Series File http://soils.usda.gov/technical/classification/osd/index.html; verified 23 May 2005) and the pedons sampled (Table 1) differ from those reported in Parsons et al. (1981) because of revisions in Soil Taxonomy (Soil Survey Staff, 1999). The pedons were also sampled in 1978 before the 1980 St. Helens eruption. The 1980 eruption of Mount St. Helens added another 2 to 3 mm of ash to the soils (C.J. Weisel, Soil Scientist, NRCS, personal communication, 1980).

Laboratory Methods

Methods used are referenced and briefly described in the Soil Survey Methods Manual (Soil Survey Laboratory Staff, 1996). Particle-size analysis (3A1) was by sieve and pipette analyses, and organic C (OC) (6A1c) by acid-dichromate digestion and automatic $FeSO_4$ titration. Iron and Al were extracted by dithionite-citrate (6C2b and 6G7a, respectively), sodium pyrophosphate (6C5a and 6G5a, respectively), and ammonium oxalate (6C9a and 6G10, respectively). Optical density (8J) and Si (6V2) were also measured on the ammonium oxalate extracts. Allophane was estimated as 8.3 × Si extracted by ammonium oxalate (Parfitt and Hemni, 1982; Parfitt, 1990). Phosphorus-retention was determined by the New Zealand method (6S4). Bulk density was measured by the clod method (4A1d).

Clay mineralogy was determined by x-ray diffraction analysis (7A2i). Tephra percentages were based on counts of 300 grains from the very fine sands (0.05–0.10 mm, 7B1). Tephra percentages include glass shards, glass coated grains of feldspars and other minerals, and glassy aggregates. Bases were extracted with ammonium acetate at pH 7.0 by an automatic extractor (5B5). The cation-exchange capacity (CEC) at pH 7.0 was measured by steam distillation of NH_4, following cation displacement (5A8b). Base saturation (BS) was by the sum of cations method ($BS_{8.2}$) (5C3). Soil pH was measured in a suspension of 1 g of soil in 50 mL of 1 *M* NaF and in 0.01 *M* $CaCl_2$ solution at a 1:2 soil/solution ratio. Al was extracted by 4 *M* KOH at room temperature and titrated with 0.1 *M* HCl (Holmgren and Kimble, 1984).

Statistical analyses were by the Statgraphics Plus for Windows Version 1.1 (Manugistics, 1994)[1]. Thin sections were prepared by the method of Innes and Pluth (1970). They were described using the nomenclature of Brewer (1976), Stoops and Jongerius (1975), Brewer and Pawluk (1975), and Brewer et al. (1983).

RESULTS AND DISCUSSION

We first examine the soils by terrace level and then discuss differences and similarities. Because of their coarse texture and fragment content, we were unable to measure bulk density on all samples (Table 1). To complete the bulk density data set for Table 1, we modeled bulk density using data from the eight Kootenai, Bonner, and Rathdrum pedons reported in Table 1, plus a Kootenai soil from T3 and Bonner and Rathdrum soils from T5. The A and Bw horizons for the Kootenai soils on the older terraces are slightly thicker than those of the younger terraces. Only Kootenai on terrace T2, Bonner on terrace T1, and Rathdrum on terraces T4 and T1 have a bulk density of 0.90 g cm^{-3}or less. Bonner soils on T4 have slightly thicker sola than those on T1 and also have slightly higher bulk densities, 0.88 vs. 0.82 g cm^{-3} by terrace level, respectively. Rathdrum soils are ashy and have low bulk densities on the T4 and T1 levels, 0.72 and 0.62 g cm^{-3}, respectively. The mean tephra content of the tephra-influenced material (A and B horizons) of Kootenai and Bonner soils on terraces T4 and T5 (45%) is significantly more than that in Kootenai and Bonner on the terraces T1 and T3 (11%), but less than that in Rathdrum (77%) (Fig. 5 and Table 1). The tephra in all these soils is somewhat weathered as observed in the A1 horizon of Kootenai (Fig. 6).

Allophane contents as high as 95 g kg^{-1} occur in one Rathdrum horizon (Table 2). A and B horizons of a Bonner pedon on a lower terrace (T4) contain more allophane than those of a Bonner pedon on the highest terrace (T1). Amounts of allophane are ≤5 g kg^{-1} in A and B horizons of Kootenai on T1, but are nearly 70 g kg^{-1} on T4. Crystalline minerals dominate the samples of clays analyzed in the 2C horizons of the soils (Ta-

[1] Use does not constitute endorsement by the USDA–NRCS.

Fig. 3. Bonner profile sampled on terrace T1. The scale is in decimeters.

ble 2). Optical densities of the ammonium oxalate extracts in these soils tend to be higher in surface horizons than in the B horizons. Other spodic horizon indicators such as Al_o + 1/2 Fe_o and Na pyrophosphate to dithionite-citrate extractable ratios of Fe & Al also remain low. Spodic horizon development therefore is not advanced (Daly, 1982; Soil Survey Staff, 1999).

Fig. 4. Rathdrum profile on terrace T1. The scale is in decimeters.

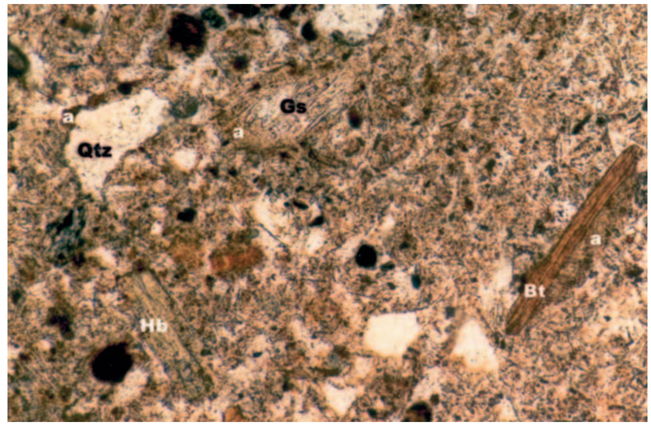

Fig. 6. Photomicrographs of the A1 horizon of the Kootenai soil on terrace T1 in plain light showing a sand-size quartz grain (upper left, QTZ) in an isotic plasmic fabric that includes some glass shards (Gs). The c/f distribution is gefuric. The coating on the Quartz and schist grain (right center, Bt) is isotropic (amorphous) (a). The weathered part (vermiculite) of the schist grain is anisotropic and partly pleochoic. Frame width (F.W.) = 2.0 mm.

Weathering Differences of Terrace Soils

In terrace sequences, commonly the highest terrace is the oldest and most weathered and the lowest is the youngest and least weathered (e.g., Gamble et al., 1970; Torrent et al., 1980; Bull, 1990; Harrison et al., 1990; Nettleton and Chadwick, 1991; Daniels and Hammer, 1992, p. 17–18). Parsons et al. (1981) considered that to be the case in their study of these terraces. Note that the degree of weathering of the Rathdrum soils on the younger (T4) and older (T1) terraces is about the same as indicated by their NaF pH and allophane content (Tables 1 and 2). This is to be expected considering that most of the tephra may be Mazama and fell across all of the terraces more or less evenly. The Rathdrum soil

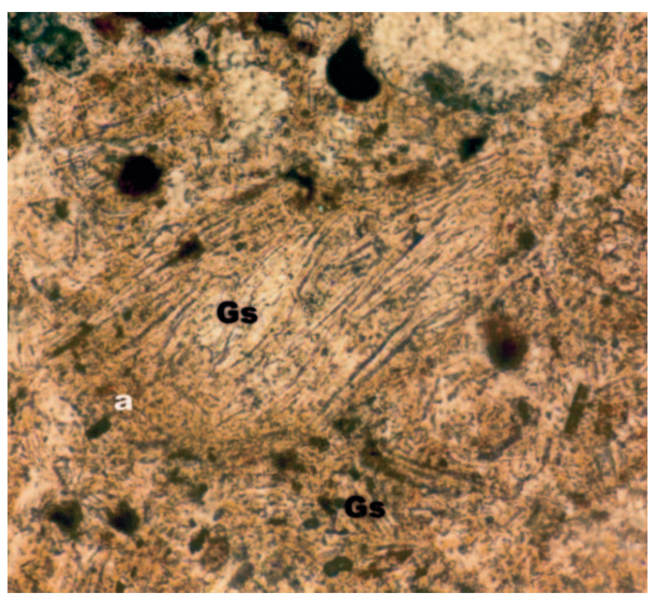

Fig. 7. Photomicrographs of a glass shard (Gs) of the Kootenai soil on terrace T1 in plain light showing its amorphous weatherin rind (a). Frame width = 0.5 mm

Table 1. Selected physical and chemical data for the soils.†

Terrace level	Soil horizon	Depth	>2-mm whole soil weight	Tephra in 0.05–0.10 mm‡	NaF pH	Bulk density at 33 kPa	1500 kPa water to clay	OC	1500 kPa H_2O (dry)	CEC ammonium acetate	CEC sum of cations	Base saturation sum of cations	pH 0.01 *M* $CaCl_2$ 1:2 soil/water ratio
		cm	%	%		g cm^{-3}	ratio	g kg^{-1}	g kg^{-1}	cmol kg^{-1}		%	
T1	Kootenai Taxadjunct (S78ID017-001), a Vitrandic Haploxerept												
	A	0–5	70	15	8.4	0.9§	1.55	74.5	153	32.6	41.7	41	5.0
	AB	5–15	69	15	9.8	1.0§	1.04	31.0	86	18.3	24.7	39	5.2
	Bw1	15–28	68	8	10.2	1.0§	1.05	21.0	67	15.9	21.4	36	5.4
	Bw2	28–38	64	3	8.9	0.99	0.63	4.5	54	10.0	10.9	54	5.3
	Bw3	38–66	80	9	8.8	1.2§	0.96	4.5	43	8.2	8.5	51	5.2
	2C	66–152	91	3	7.8	1.2‡	1.29	1.4	31	7.2	6.9	64	5.3
T2	Kootenai Taxadjunct (S78ID017-004), a Vitrandic Haploxerept												
	A	0–3	32	12	8.5	0.8§	1.49	78.2	134	33.1	42.0	53	5.5
	AB	3–10	44	7	9.2	0.8§	0.90	33.0	86	21.4	27.6	51	5.4
	Bw1	10–25	43	13	9.3	0.90	0.83	14.0	70	13.5	17.9	43	5.3
	Bw2	25–46	51	1	8.2	0.84	0.54	3.6	53	9.7	10.9	58	5.0
	Bw3	46–71	73	2	7.5	1.0§	0.75	2.2	46	12.9	13.2	73	5.1
	2C1	71–104	78	4	7.7	1.0§	2.00	6.1	50	16.8	17.2	76	5.3
	2C2	104–112	66	1	7.5	1.2§	NR¶	0.7	33	10.1	9.9	83	5.6
	2C3	112–152	85	2	7.7	1.1§	NR¶	2.9	45	20.1	20.1	85	5.6
T4	Kootenai (S78ID017-007), a Typic Vitrixerand												
	A	0–5	9	47	9.5	0.76	5.83	106.0	169	34.7	40.9	45	5.6
	AB	5–13	20	43	10.6	0.9§	6.61	37.9	119	23.1	33.5	50	5.9
	Bw1	13–28	17	39	11.0	1.25	8.00	26.9	104	16.4	25.6	34	5.5
	Bw2	28–43	37	56	10.6	1.0§	NR¶	13.1	75	9.5	16.2	16	5.3
	Bw3	43–58	27	7	8.6	1.2§	NR¶	2.1	32	5.3	6.2	52	5.0
	2C1	58–81	82	1	7.5	1.3§	1.21	1.3	29	7.7	7.7	74	5.0
	2C2	81-153	74	3	7.3	1.3§	NR¶	0.4	18	4.7	5.0	78	5.3
T5	Kootenai (S78ID017-009), a Typic Vitrixerand												
	A	0–3	16	71	9.8	0.6§	4.21	113.0	244	41.8	56.7	50	ND#
	A2	3–15	20	59	10.6	1.20	0.85	32.2	128	19.8	34.4	28	5.7
	Bw1	15–36	66	59	10.3	1.00	1.04	18.1	83	11.7	18.3	32	5.5
	2Bw2	36–46	57	15	8.1	1.1§	0.68	4.3	56	9.8	11.5	67	5.7
	2C1	46–66	82	20	8.4	1.2§	0.85	2.9	56	11.4	13.2	76	6.1
	2C2	66–152	94	1	7.6	1.2§	0.75	1.1	40	10.3	11.0	85	6.1
T1	Bonner (S78ID017-002), a Typic Vitrixerand												
	A	0–3	33	19	10.1	0.9§	1.81	85.0	121	25.5	31.7	49	5.8
	Bw1	3–13	32	17	10.2	0.9§	1.30	42.3	73	17.1	24.3	44	5.7
	Bw2	13–35	31	20	10.2	0.82	1.27	20.9	71	12.9	18.5	35	5.4
	Bw3	35–48	58	9	9.2	0.72	0.68	4.3	50	7.6	9.6	52	5.4
	2C1	48–68	82	6	7.9	0.97	1.16	1.6	43	8.6	8.5	68	5.3
	2C2	68–112	87	2	7.7	1.2§	0.76	1.6	34	6.5	7.2	67	5.4
	2C3	112–152	42	6	7.6	1.3§	0.40	1.0	29	5.2	5.7	74	5.6
T4	Bonner (S78ID017-008), a Typic Vitrixerand												
	A	0–4	18	54	9.5	0.68	3.63	135.3	203	36.9	49.0	38	ND#
	Bw1	4–20	27	49	10.6	0.9§	2.56	25.4	100	18.9	28.4	26	5.5
	Bw2	20–48	29	53	10.6	0.94	5.82	13.4	99	13.4	21.7	18	5.4
	Bw3	48–69	42	47	10.4	1.0§	2.06	6.3	68	9.6	14.3	27	5.5
	Bw4	69–89	43	45	10.3	0.80	2.72	5.9	68	9.4	14.2	28	5.4
	2C1	89–152	77	5	7.6	1.3§	1.38	0.8	22	4.1	4.4	75	5.3
T1	Rathdrum (S78ID017-003), a Typic Udivitrand												
	A	0–3	3	66	8.6	0.6§	2.34	178	225	43.3	54.5	33	ND#
	Bw1	3–13	17	74	10.4	0.77	4.13	45.3	128	25.8	36.0	44	5.9
	Bw2	13–25	23	73	10.6	0.8§	3.44	14.9	117	16.1	24.4	36	6.0
	C1	25–43	20	78	10.6	1.14	4.04	15.6	105	14.9	25.1	31	6.0
	C2	43–71	14	78	10.5	0.8§	3.29	9.9	112	14.0	22.1	35	5.9
	C3	71–107	16	81	10.1	0.9§	6.17	4.0	74	8.0	12.3	26	6.4
	2C4	107–165	45	4	8.9	1.3§	0.80	1.7	39	6.4	7.7	60	5.3

Continued next page.

Table 1. Continued.

Terrace level	Soil horizon	Depth	>2-mm whole soil weight	Tephra in 0.05–0.10 mm‡	NaF pH	Bulk density at 33 kPa	1500 kPa water to clay	OC	1500 kPa H_2O (dry)	CEC ammonium acetate	CEC sum of cations	Base saturation sum of cations	pH 0.01 *M* $CaCl_2$ 1:2 soil/water ratio
		cm	%	%		g cm^{-3}	ratio	g kg^{-1}	g kg^{-1}	cmol kg^{-1}		%	
T4	Rathdrum (S78ID017-006), a Typic Udivitrand												
	A	0–1	–	75	8.9	0.3§	NR¶	187	501	28.7	56.1	23	ND#
	A2	1–8	2	71	10.5	0.8§	6.11	23.8	165	19.0	31.1	35	6.0
	Bw	8–28	2	79	10.4	0.8§	5.20	11.3	104	13.3	22.9	26	5.7
	C1	28–46	13	73	10.4	0.9§	7.07	10.7	106	11.9	20.7	25	5.6
	C2	46–66	–	93	10.2	0.8§	NR¶	4.4	99	8.0	14.4	27	5.6
	C3	66–94	–	86	9.8	0.9§	NR¶	2.4	68	5.5	9.1	34	5.8
	2C4	94–152	17	6	7.6	0.89	1.58	0.5	38	7.1	8.2	74	5.4

† Soil Survey Staff (1999).
‡ Index of refraction ranges between 1.48 and 1.50. Most tephra grains are between 1.490 and 1.495.
§ Estimated from bulk density at 33kPa = 1.39 − 0.0063 × silt content (%) − 0.0022 × OC − 0.0132 × 1500 kPa water, r^2 = 0.25, SE = 0.19, n = 42, samples include some Kootenai, Bonner, and Rathdrum soils not reported in this table.
¶ Ratio not reported as the measured clay content approaches zero making the 1500 kPa water/clay ratio approach infinity.
# Not measured.

on the youngest terrace (T5) however, seems to be less weathered relative to the others as indicated by its lower 1500 KPa water, CEC8, ΔCEC, and allophane contents (Table 3). One reason is suggested by its lower chroma (Kimble and Nettleton, 1987, p. 188), an indication either of restricted drainage, or of a higher water table and reduced leaching. Restricted drainage is unlikely considering the texture of the deposit. The closely associated floodplain Histosol supports the higher water-table view. Hence we attribute its lesser weathering to reduced leaching.

Allophane and tephra contents of the soils are positively related to each other and to 1500 KPa water, NaF pH, CEC sum of cations, ΔCEC, P retention and negatively related to the BS sum of cations (Table 4). The vfs fractions of the Rathdrum soils on terraces T1 and T4 are mostly tephra (Table 1). The physical and chemical properties of these Rathdrum soils show no weathering trends relative to terrace age where leaching potential is believed to be equivalent. This suggests that the weathering differences noted between Bonner and Kootenai soils by terrace level are mostly a result of differences in the tephra content of the parent materials.

Tephra Distribution on the Terraces

The tephra-influenced material of Rathdrum soils on T1 and T4 has a vfs tephra content >60% (Table 1). The vfs content of the three horizons of the Rathdrum soil on T5 have tephra contents of >80% (Kimble and Nettleton, 1987, p. 191). The Rathdrum soils have accumulated about four times as much tephra as has been estimated to have fallen. In the Rathdrum soils then, terrace level had no impact on the composition of the deposit. The higher tephra contents of the Rathdrum soils in the troughs, as compared with the Kootenai and Bonner on the current ripple ridges, may be a result of erosion of tephra from the ridges and its deposition in the troughs (Parsons et al., 1981). The Kootenai and Bonner soils on T4 and T5 have higher tephra contents than the same soils on T1-T3 (Fig. 5). Only about 20 to 50% of the 15 cm of tephra calculated to have fallen on Kootenai and Bonner on the older terraces (T1–T3) remains (Table 3). The younger ones (T4 and T5), assuming that the original distribution of tephra was uniform, have retained all that that fell or have gained some. One explanation is for the tephra fall to have occurred on snow-covered terraces followed by thawing and erosion; a second explanation is for subsequent reworking by wind, less likely in these forested landscapes. Erosion, in any case, would be expected to be greater on the older terraces than on the younger ones because the older terraces have a greater microrelief than the younger ones (Parsons et al., 1981). The tephra eroded from the crests and side slopes of the giant current ripples would have been deposited mostly in the associated, partly closed troughs. Some may have been redeposited in Bonner on the lowest terraces. The tephra deposits in the Rathdrum soils are 13 cm thicker on terrace T1 than on T4 (Table 1). This greater deposition

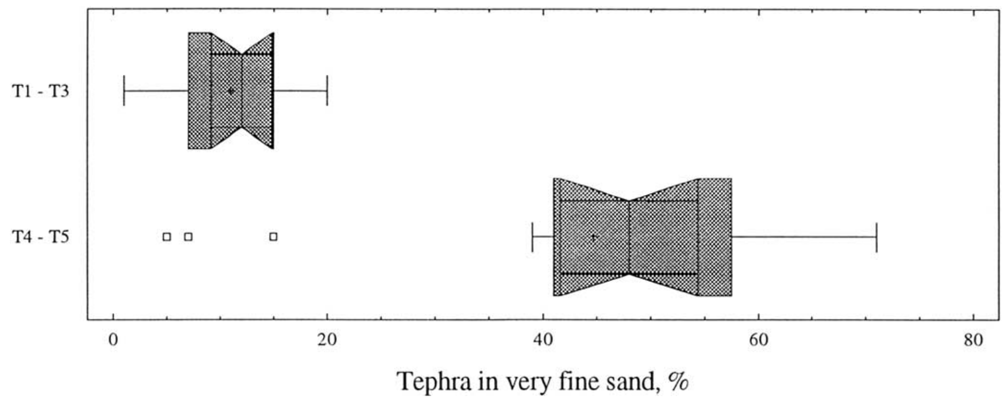

Fig. 5. Box and whisker plot of the tephra content of the very fine sand of the A and B horizons of the Bonner and Kootenai soils on the higher terraces (T1–T3) and the lower terraces (T4–T5). Far-outside points that lay more than 3.0 times the interquartile range above or below the box are shown as small squares.

on the Rathdrum soil on the older terrace further supports the view that greater erosion has occurred on the Bonner and Kootenai soils on the older terraces. The 112-cm deposit on T5 matches the thickness of that on T1 again may have resulted from redeposition of tephra from the higher terraces. Observations of the 1980 Mount St. Helens volcanic ash suggest that erosion and redeposition of tephra would have occurred in the first year or so before vegetation became established; hence weathering of the ash would have begun after vegetation was reestablished so that the exposure time to weathering may have been the same across the five terraces.

Chemical Properties of the Soils

The NaF pHs, Alo, allophane contents, and P retention data of the A1 horizons tend to be lower than those of subjacent horizons (Table 1). This may be a result of the affinity of organic matter for Al^{3+} and of the A1 horizon's much higher organic matter values. Organic matter is known to complex Al^{3+} tightly enough to prevent its displacement by neutral salt solutions (Thomas, 1975; Nelson and Nettleton, 1975; Nettleton et al., 1987). Alternatively, the Al^{3+} may have been removed from the horizon as soluble Al-humus complexes thus lowering the Al^{3+} activity somewhat like McDaniel et al. (1997) described in the formation of non-allophanic E horizons in tephra-influenced soils in Idaho. They also observed the lower NaF pH in soils at elevations above any in our study area. The E horizons were not detected in the soils we studied.

The Bw horizon NaF pH of the Bonner pedon on terrace T4 is higher than that of Bonner on terrace T1 (Table 1). This may be a result of the higher tephra content of Bonner on T4 (Table 1). Note that the NaF pH values of Rathdrum are similar on T1 and T4 where tephra contents are similar (Table 1). There is a statistically significant positive relationship between these variables (Table 4) as well. The correlation is improved when only the B and C horizons are included.

$$\begin{aligned} \text{NaF pH} &= 8.2 + 0.0325 \times \text{tephra\%}, \\ r^2 &= 0.66,\ \text{SE} = 0.8, \\ n &= 40,\ \text{F-Ratio} = 71.9, \\ \text{probability level} &= 0.001 \end{aligned}$$

The other properties such as OC, 1500 KPa water, CEC sum of cations (Table 1) and dithionite-citrate extractable Fe and Al and clay mineralogy (Table 3) do not appear to differ consistently among the soils by terrace level. The accumulations of OC, 1500 KPa water, CEC sum of cations on a whole soil basis to depths of 150 cm also do not have a consistent pattern for these soils (Table 3).

Ammonium oxalate extractable Fe_o, Si_o, and Al_o contents and hence the allophane contents tend to be greater in Bonner soils on T4 and T5 than those on T1 (Tables 2 and 3). The accumulation of allophane and the difference in the $CEC_{8.2}$ and CEC_7 (ΔCEC), another measure of allophane content, is an order of magnitude higher in the Bonner soil on T4 than it is in the Bonner soil on T1 (Table 3). The ΔCEC for the Kootenai soils increases from T1 and T2 to T5 and allophane content increases from T1 to T5. Note that the allophane content and the ΔCEC for the Rathdrum soils remain nearly unchanged between T1 and T4. Because the tephra content of the Rathdrum soils remains the same across the terraces and that of Bonner and Kootenai increases from the older to the younger terraces, these differences in properties may be more a result of the higher tephra content of the younger terraces (Table 1) than of any difference in the degree of weathering. Again we think that the Rathdrum on T5 contains less allophane, 1500 KPa water, and Δ CEC because of less leaching as indicated by its lower chroma (Table 4).

Micromorphology

Both isotropic and anisotropic weathering products are present in the Bonner and Kootenai soil fabrics.

Table 2. Some extractable metal cations and related measurements of the soils and K_2O content and x-ray diffraction data for clays.

Horizon	Depth	Dithionite-citrate extractable: Fed	Dithionite-citrate extractable: Ald	Na pyrophosphate Extractable: Fep	Na pyrophosphate Extractable: Alp	Fep & Alp/Fed & Ald ratio	Fep & Alp/Clay ratio	Optical density	Acid oxalate extraction: Feo	Acid oxalate extraction: Sio	Acid oxalate extraction: Alo	Acid oxalate extraction: Allophane	P retention	Total K_20	Clay mineralogy†: X ray diffraction
	cm	g kg^{-1}							g kg^{-1}				%	g kg^{-1}	
T1 Kootenai Taxajunct loamy-skeletal, isotic, frigid Vitrandic Haploxerept															
A	0–5	10	4	3	3	0.4	0.1	0.22	4.0	0.3	3.6	2.5	26	7.0	MI
AB	5–15	12	4	2	3	0.3	0.1	0.32	5.8	0.6	5.9	5.0	30	ND	
Bw1	15–28	11	4	2	3	0.3	0.1	0.21	5.1	0.6	5.4	5.0	32	ND	
Bw2	28–38	10	1	1	1	0.2	<0.1	0.07	2.8	<0.1	1.9	<0.8	28	10.0	VR2, ~MI2, KK1
Bw3	38–66	8	1	1	1	0.2	<0.1	0.08	2.9	0.1	1.8	0.8	25	ND	
2C	66–152	9	1	1	1	0.2	0.1	0.05	1.8	<0.1	0.7	<0.8	25	ND	
T5 Kootenai Taxadjunct ashy over sandy or sandy-skeletal, glassy over mixed, frigid Typic Vitrixerand															
A	0–3	9	5	2	4	0.4	0.1	0.54	3.8	3.9	10.6	32.4	41	8	NX
A2	3–15	11	5	1	3	0.3	<0.1	0.28	5.2	8.4	18.0	69.7	62	5	NX
Bw1	15–36	11	3	1	2	0.2	<0.1	0.12	3.3	5.1	10.3	42.3	46	ND	
2Bw2	36–46	9	1	1	1	0.2	<0.1	0.10	2.3	1.0	2.3	8.3	21	18	VR2, MI2, KK1
2C1	46–66	8	1	1	<1	0.1	<0.1	0.06	1.6	0.8	1.5	6.6	17	ND	
2C2	66–152	7	<1	1	<1	0.1	<0.1	0.02	1.0	0.4	0.5	3.3	17	25	MI3, KK3, VR2, MT1, CL1
T1 Bonner ashy over sandy or sandy-skeletal, glassy over mixed, frigid Typic Vitrixerand															
A	0–3	11	4	3	4	0.5	0.1	0.17	4.5	2.1	6.2	17.4	29	9	NX
Bw1	3–13	11	4	2	3	0.3	0.1	0.14	3.9	2.0	7.2	16.7	37	9	NX
Bw2	13–35	11	4	2	3	0.3	0.1	0.20	3.9	2.0	6.1	16.6	36	ND	
Bw3	35–48	10	1	1	1	0.2	<0.1	0.04	2.1	1.0	2.0	8.3	15	13	MI2, KK1, VR1
2C1	48–68	7	1	1	1	0.3	0.1	0.05	3.1	1.0	1.0	8.3	5	ND	
2C2	68–112	7	1	1	<1	0.1	<0.1	0.02	1.5	0.2	0.5	1.7	5	ND	
2C3	112–152	9	1	1	<1	0.1	<0.1	0.03	1.7	0.2	0.4	1.7	3	ND	
T4 Bonner ashy over sandy or sandy-skeletal, glassy over mixed, frigid Typic Vitrixerand															
A	0–4	9	4	<1	<1	0.1	<0.1	0.36	4.2	2.9	9.3	24.1	38	4	NX
Bw1	4–20	10	5	<1	3	0.3	0.1	0.23	5.6	8.9	20.3	73.9	66	ND	
Bw2	20–48	11	4	<1	2	0.2	0.2	0.18	4.9	11.6	20.7	96.3	58	ND	NX
Bw3	48–69	9	2	<1	1	0.2	0.1	0.12	3.7	8.3	14.2	68.9	42	ND	
Bw4	69–89	9	2	<1	1	0.2	0.1	0.10	3.0	6.0	10.9	49.8	37	ND	
2C	89–152	5	<1	<1	3	0.8	0.3	0.03	1.8	0.5	0.7	4.2	30	22	VR3, MI3, KK2, CL1
T1 Rathdrum ashy, glassy, frigid Typic Vitrixerand															
A	0–3	7	3	3	2	0.5	0.1	0.44	3.4	1.9	5.9	15.8	29	5	NX
Bw1	3–13	9	5	2	3	0.4	0.2	0.25	4.3	6.8	14.9	56.4	54	ND	NX
Bw2	13–25	9	4	1	2	0.2	0.1	0.18	4.2	8.3	16.5	68.9	58	5	NX
C1	25–43	10	4	1	2	0.2	0.1	0.16	4.4	9.0	17.9	74.7	66	ND	NX
C2	43–71	9	3	1	2	0.3	0.1	0.15	4.2	9.5	17.6	78.8	61	ND	
C3	71–107	6	2	1	1	0.3	0.2	0.07	2.4	5.4	10.6	44.8	42	ND	
2C4	107–165	8	1	1	<1	0.1	<0.1	0.03	2.2	0.5	1.0	4.2	15	ND	
T4 Rathdrum ashy, glassy, frigid Typic Vitrixerand															
A	0–1	8	5	3	3	0.5	1.0	0.62	3.5	1.9	6.4	15.8	33	ND	
A2	1–8	9	6	2	3	0.3	0.2	0.17	4.5	7.4	15.7	61.4	60	6	NX
Bw	8–28	9	4	1	2	0.2	0.2	0.16	5.7	11.5	20.4	95.4	61	ND	
C1	28–46	8	3	1	2	0.3	0.2	0.12	3.9	9.7	17.1	80.5	54	ND	NX
C2	46–66	6	2	1	1	0.3	1.0	0.06	3.0	8.6	15.9	71.4	39		
C3	66–94	5	1	1	1	0.3	2.0	0.04	1.6	4.3	9.1	35.7	33	ND	
2C4	94–152	8	<1	1	<1	0.1	<0.1	0.04	1.9	0.5	0.5	4.2	28	15	

† Clay mineralogy: MI, clay mica; VR, vermiculite; MT, smectite; KK, kaolinite; NX, amorphous to X-ray; CL, chlorite; 1,2,3 are for the relative peak height.

Table 3. Accumulation of organic C (OC), 1500 KPa water, cation-exchange capacity sum (CEC_{sum}), and ΔCEC† and tephra in the three soils to a depth of 150 cm.

	Spokane Flood Terrace				
Soil data	TI	T2	T3	T4	T5
	Bonner				
OC, kg m^{-2}	10	NS‡	NS‡	12	5
1500 KPa water kg m^{-2}	42	NS‡	NS‡	67	42
CEC_{sum}, cmol m^{-2}	100	NS‡	NS‡	159	75
ΔCEC, cmol m^{-2}	21	NS‡	NS‡	49	24
Allophane, kg m^{-2}	7	NS‡	NS‡	53	19
Tephra, kg m^{-2}	88	NS‡	NS‡	367	NS‡
Tephra/tephra deposited¶	0.52	NS‡	NS‡	2.18	NS‡
	Kootenai				
OC, kg m^{-2}	7	6	8	12	8
1500 KPa water kg m^{-2}	27	39	36	47	40
CEC_{sum}, cmol m^{-2}	70	114	69	118	97
ΔCEC, cmol m^{-2}	13	12	20	17	30
Allophane, kg m^{-2}	1	NA§	NA§	NA§	15
Tephra, kg m^{-2}	37	30	46	181	173
Tephra/tephra deposited¶	0.22	0.18	0.27	1.07	1.03
	Rathdrum				
OC, kg m^{-2}	13	NS‡	NS‡	7	5
1500 KPa water kg m^{-2}	92	NS‡	NS‡	94	75
CEC8, cmol m^{-2}	193	NS‡	NS‡	173	93
ΔCEC, cmol m^{-2}	63	NS‡	NS‡	62	29
Allophane, kg m^{-2}	50	NS‡	NS‡	54	26
Tephra, kg m^{-2}	634	NS‡	NS‡	671	NS‡
Tephra/tephra deposited¶	3.77	NS‡	NS‡	3.99	NS‡

† *f* ΔCEC, cmol m^{-2} = CEC_8, cmol m^{-2} − CEC_7, cmol m^{-2}.
‡ No soils were sampled on these terraces.
§ These analyses were not run.
¶ Tephra/tephra deposited, assuming that 15 cm was deposited with a D_b of 1.12 g cm^{-3} when depths were measured (for a total of 168 kg m^{-2}). The D_b was measured on a Mt. St. Helens 1980 ash that had been poured dry into a 7.6-cm (3-inch) cylinder, saturated and then leached before measurement.

The A1 horizons of these soils on T1 have single-space porphyric related distribution patterns as seen here for Kootenai (Fig. 6). Matrices are silty and include some tephra. The A1 horizons of Kootenai and Bonner on T4 also have a single-space porphyric related distribution patterns. However, their matrices have more silt and vfs-size tephra than the Kootenai and Bonner soils on T1.The tephra examined has refractive indices of 1.48 to 1.50 (Table 1). This is in the range for Glacier Peak Ash, but hydration of the glass increases the index, and there are other ashes in the index and time ranges (Wilcox, 1965). The surface of the glass has a brown isotropic (amorphous) weathering product (Fig. 7). The sand grain at right center of Fig. 6 is a weathered, granitic skeleton grain. The pleochroic and anisotropic part of this grain is part biotite and part vermiculite. On the surface of this skeleton grain there is an isotropic coating. Most of the Bw horizons of the Kootenai and Bonner soils have skeleton grains with isotropic coatings. The lowest parts of the Bw horizons of these two soils also tend to have chitonic related distribution patterns. The plasma surrounding the skeleton grains is isotropic.

Location of the weathering products in the upper parts of the profiles suggests that the current weathering is toward amorphous material. This fits the pattern found in soil clays in tephra-influenced materials in northern Idaho where smectite dominates at an elevation of 1830 m and allophanic materials at elevations of 1450 and 960 m (McDaniel et al., 1993). The anisotropic weathering products are within skeleton grains, whereas the isotropic weathering products are within the matrix and on surfaces of skeleton grains. The anisotropic weathering products may have been inherited from the parent material because no micromorphic differences were observed in the degree of weathering of primary crystalline grains in the soils on the different terraces.

CONCLUSIONS

We agree with the earlier conclusion that reworking of tephra by water accounts for the thick deposits in troughs of the giant ripple marks. However, the erosion cycles producing the thick tephra deposits left more tephra on ridges of the youngest terraces than on the oldest ones. We attribute this difference to the greater relief of the oldest terraces. This greater tephra content of the Kootenai and Bonner soils on the younger terraces, likely produced the NaF pH and other amorphous material related property differences noted between these soils on the younger and older terraces. Although the difference in exposure of the coarse-textured outwash materials below the tephra on the highest and lowest terraces may be as great as 6000 yr, we found no differences in the degree of weathering of these coarse materials by terrace level and no differences in welding influence on the soils. Since soils on ridges of the older terraces contain less tephra and less amorphous material and related properties than soils on lower terraces, consideration should be given in update mapping to differentiating these soil series by terrace level.

Table 4. Correlation matrix of some properties of the Kootenai, Bonner, and Rathdrum soils.†

	Sample correlations							
Item phane	1500 KPa	NaF pH	CEC sum	ΔCEC	P retention	BS sum	Allophane	Tephra (VFS)
	g kg^{-1}		cmol kg^{-1}	cmol kg^{-1}	%	%	g kg^{-1}	%
Allophane	0.2810	0.8213	0.3579	0.5409	0.8872	−0.7489	1.0000	
No. of Samples	(57)	(57)	(57)	(57)	(57)	(57)	(57)	
Probabilities	0.0342	0.0000	0.0063	0.0000	0.0000	0.0000	0.0000	
Tephra	0.4992	0.7049	0.4109	0.6305	0.7368	−0.4900	0.7994	1.0000
No. of Samples	(66)	(66)	(66)	(66)	(44)	(66)	(44)	(66)
Probabilities	0.0000	0.0000	0.0006	0.0000	0.0000	0.0000	0.0000	0.0000

† CEC, cation-exchange; BS, base saturation; VFS, very fine sand.

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